

FIBER OPTIC CURVATURE SENSOR FOR TOWED HYDROPHONE ARRAYS

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT (1) GREGORY H. AMES, and (2) ANTONIO L. DEUS III, citizens of the United States of America, employees of the United States Government, and residents of (1) Wakefield, County of Washington, State of Rhode Island, (2) Saunderstown, County of Washington, State of Rhode Island, have invented certain new and useful improvements entitled as set forth above of which the following is a specification.

MICHAEL J. MCGOWAN, ESQ.
Reg. No. 31042
Naval Undersea Warfare Center
Division Newport
Newport, RI 02841-1708
TEL: 401-832-4736
FAX: 401-832-1231



23523

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3 FIBER OPTIC CURVATURE SENSOR FOR TOWED HYDROPHONE ARRAYS

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5 STATEMENT OF GOVERNMENT INTEREST

6 The invention described herein may be manufactured and used
7 by or for the Government of the United States of America for
8 governmental purposes without the payment of royalties thereon
9 or therefore.

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CROSS REFERENCE TO OTHER PATENT APPLICATIONS

This patent application is co-pending with two related
patent applications entitled FIBER OPTIC PITCH OR ROLL SENSOR
(Attorney Docket No. 78381) and MULTIPLEXED FIBER LASER SENSOR
SYSTEM (Attorney Docket No. 78371), by the same inventors as
this application.

17

18 BACKGROUND OF THE INVENTION

19 (1) Field of the Invention

20 The invention relates to a device and method for sensing
21 the curvature of a towed array. The device of the present
22 invention, in combination with other sensors, may be used to
23 determine the shape of a towed hydrophone array.

1 (2) Description of the Prior Art

2 Optical fibers have been used in a variety of sensors. For
3 example, U.S. Patent Nos. 4,654,520; 4,812,645; and 4,927,232,
4 all to Griffiths, illustrate structural monitoring systems which
5 have an optical fiber securely and continuously fastened to a
6 structure such as a pipeline, offshore platform, bridge,
7 building, or a dam or to a natural object. A light signal is
8 passed into one end of the optical fiber. Any physical movement
9 of the structure, or sectional movements along the optical fiber
10 path, such as deflection, bending, displacement, or fracture of
11 the structure affects the optical fiber. As a consequence,
12 detectable changes occur in the electro-optical signature or in
13 the light signal transmission.

14 U.S. Patent No. 5,321,257 to Danisch illustrates a fiber
15 optic bending and positioning sensor which is composed of a
16 fiber optic or light wave guide for attachment to the member
17 which is to be bent or displaced. Light is injected at one end
18 and detected at the other end. Bending of the fiber results in
19 light loss through a surface strip or band, along one side of
20 the fiber, this loss being detected. The loss of light
21 detection is used to produce indication of bending or
22 displacement. Two or more light guides can be oriented to give
23 indication of the direction of bending or displacement.

1 One of the deficiencies of these systems however is that
2 the optical fiber(s) used in the sensor is/are attached directly
3 to the structure whose behavior is being observed.

4 Some towed hydrophone arrays require precise determination
5 of their shape in the water. This has been done in the past
6 with gimbaled heading sensors. Such sensors are quite
7 expensive. They are unsuitable in today's environment where one
8 needs to reduce cost in a towed array. It is also desirable in
9 modern towed arrays to provide shape sensing that is compatible
10 with optical hydrophones and that is relatively inexpensive to
11 perform.

12 An alternative way to determine array shape is by curvature
13 sensors and either roll or twist sensors. It has been proposed
14 to use fiber optic sensors to sense curvature. Such sensors
15 embed optical fibers containing Bragg gratings in the hose wall
16 of the towed array. The Bragg gratings sense the strain in the
17 hose wall when the array is bent and the differential strain
18 from the outside to the inside of the bend permits calculation
19 of the curvature. However, the strain seen in the hose wall as
20 the array passes over small diameter handling sheaves can exceed
21 the survival strain of an optical fiber. It has been suggested
22 to reduce the strain seen by winding at a pitch angle, but that
23 approach is awkward. It has also been suggested to reduce
24 strain by minimizing the distance each fiber is placed from the

1 centerline of the array. The disadvantage of all these mounting
2 schemes is that while limiting the maximum strain seen, these
3 schemes also limit the strain sensitivity achievable. One may
4 define a total dynamic range of curvature from the maximum
5 curvature of the handling system sheaves to the minimum
6 curvature associated with the ultimate array position accuracy
7 desired. This range may be 50 dB. Meanwhile, the sensor system
8 actually only has to operate in towing conditions where the
9 range of curvatures seen may be less than 30 dB.

10 Thus, there remains a need for a system which senses the
11 curvature of a towed array as well as the shape of the towed
12 array.

13 SUMMARY OF THE INVENTION

14 Accordingly, it is an object of the present invention to
15 provide a sensor system which senses the curvature of a towed
16 hydrophone array.

17 It is a further object of the present invention to provide
18 a sensor system as above which can in combination with other
19 sensors may be used to determine the shape of a towed hydrophone
20 array.

21 It is yet a further object of the present invention to
22 provide a sensor system as above which achieves high strain
23 sensitivity while limiting the maximum strain seen by the
24

1 optical fiber(s) therein so that only the operational dynamic
2 range is required of the optical fiber(s).

3 The foregoing objects are attained by the curvature sensor
4 of the present invention.

5 In accordance with the present invention, a curvature
6 sensor is provided. The curvature sensor broadly comprises a
7 bend member which bends as the array into which it is
8 incorporated bends, at least one optical fiber within the bend
9 member, and at least one detection device embedded within the at
10 least one optical fiber to detect a change in strain in the at
11 least one optical fiber.

12 A system for detecting the curvature in a towed hydrophone
13 array comprises at least two of said curvature sensors
14 positioned along the length of the array.

15 A system for also detecting the shape of the towed array
16 includes a roll sensor positioned adjacent each of the curvature
17 sensors.

18 Other details of the fiber optic curvature sensor of the
19 present invention and the systems into which it can be
20 incorporated, as well as other objects and advantages attendant
21 thereto, are set forth in the following detailed description and
22 the accompanying drawings wherein like reference numerals depict
23 like elements.

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 FIG. 1 is a schematic representation of a system for
3 sensing the curvature of a towed array and the shape of the
4 towed array;

5 FIG. 2 is a sectional view showing a first embodiment of a
6 curvature sensor in accordance with the present invention;

7 FIG. 3 is a sectional view showing a second embodiment of a
8 curvature sensor in accordance with the present invention;

9 FIG. 4 is a perspective view of a third embodiment of a
10 curvature sensor in accordance with the present invention; and

11 FIG. 5 is a sectional view of a fourth embodiment of a
12 curvature sensor in accordance with the present invention.
13

14 DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

15 Referring now to the drawings, FIG. 1 illustrates a system
16 10 for sensing the curvature and shape of a towed array.

17 Instead of a continuous optical fiber embedded into the hose
18 wall of the array, the system 10 has a plurality of single point
19 curvature sensors 12 placed at various locations along the
20 length of the towed hydrophone array 14. As depicted in FIG. 1,
21 the curvature sensors 12 may be placed quite far apart because
22 of the long transverse wavelengths of the tow cables under tow.
23 As a result, the system 10 requires fewer curvature sensors 12.
24 The system 10 further has a plurality of roll sensors 16 with

1 each roll sensor 16 being in close proximity to each curvature
2 sensor 12 so that the direction of curvature relative to the
3 surrounding environment may be determined. Because the
4 curvature sensors 12 are single point sensors, the optical
5 fiber(s) 18 that lead to and from each curvature sensor 12 may
6 be separated from the structure of the towed hydrophone array 14
7 so that the optical fiber(s) 18 do not see excessive strain as
8 the towed hydrophone array 14 is bent over small diameter
9 handling sheaves. The curvature sensors 12 of the present
10 invention are shorter than the minimum rigid length requirement
11 associated with the towed hydrophone array 14 and the handling
12 system (not shown).

13 The roll sensors 16 used in the system 10 may comprise any
14 suitable roll sensor known in the art. However, in a preferred
15 embodiment, each roll sensor 16 comprises the motion sensor
16 shown in copending U.S. Patent Application Serial No. ,
17 filed , entitled FIBER OPTIC PITCH OR ROLL SENSOR which
18 is incorporated by reference herein. Together with the
19 curvature sensors 12, the roll sensors 16 may be used in a known
20 manner to determine the shape of the towed hydrophone array 14.

21 Figure 2 illustrates a first embodiment of a curvature
22 sensor 12 in accordance with the present invention. The
23 curvature sensor 12 in this embodiment has a plurality of
24 optical fibers 18, preferably three or four optical fibers 18,

1 embedded in a bend rod 20. Each of the optical fibers 18 runs
2 longitudinally down the length of the bend rod 20. The optical
3 fibers 18 are radially distributed around the perimeter of the
4 bend rod 20. The diameter of the bend rod 20 and the diameter
5 of the optical fiber centers are determined by the strain
6 sensing requirements.

7 The separation of the optical fibers 18 acts as a lever arm
8 multiplying the strain differences seen by the optical fibers
9 18. When the bend rod 20 is bent, the optical fiber 18 on the
10 inside of the bend experiences compression, while the optical
11 fiber 18 on the outside of the bend experiences stretching. The
12 magnitude and sign of the strain difference between the two
13 optical fibers 18 gives the magnitude and sign of the curvature
14 of the array 14 at the point where the curvature sensor 12 is
15 placed.

16 The strain in each optical fiber 18 is preferably sensed by
17 embedding or incorporating a detection device 22 within each of
18 the optical fibers 18 in the bend rod 20. The detection device
19 may be an optical fiber Bragg grating written into the core of
20 the optical fiber 18. The changing strain in the optical fiber
21 18 results in a wavelength shift of the reflectivity peak of the
22 Bragg grating 18. Such a wavelength shift may then be measured
23 by any of a number of conventional means known in the art. The
24 difference in wavelength shift determines the difference in the

1 strain in a particular optical fiber 18. By comparing the
2 outputs of the Bragg gratings embedded in the optical fibers,
3 one can determine the curvature of the array at the location of
4 the curvature sensor 12.

5 In lieu of incorporating an optical fiber Bragg grating
6 into each optical fiber 18, an optical fiber Bragg grating
7 laser, such as that shown in U.S. Patent Nos. 4,761,073 and
8 5,513,913, which are hereby incorporated by reference, may be
9 embedded into each optical fiber 18. Changes in the strain in a
10 respective optical fiber 18 causes changes in the wavelength of
11 the light emitted by the optical fiber Bragg grating laser,
12 which changes can be measured by a number of means well known in
13 the art. By comparing the light emitted by the lasers
14 incorporated into the optical fibers 18, one can determine the
15 curvature of the array 14 where the curvature sensor 12 is
16 located.

17 The bend rod 20 is less than the maximum rigid length for
18 the array 14 and its handling system (not shown). The ends 24
19 and 26 of the bend rod 20 may be coupled by any of a variety of
20 means known in the art to the array structure so that the
21 bending of the array 14 results in the bending of the bend rod
22 20. For example, rigid pieces 28 may be used to couple the ends
23 24 and 26 of the bend rod 20 to the hose wall 30 of the array
24 14.

1 The bend rod 20 is preferably placed within a mount
2 assembly 32 which may be mounted in the array 14 by any of a
3 number of mounting techniques with the specific mounting
4 technique being determined by the construction of the array 14.
5 For example, the array 14 may have internal stringers 34 and the
6 mount assembly 32 may be mounted on the stringers 34. The inner
7 diameter of the mount assembly 32 preferably is greater than but
8 close to the outer diameter of the bend rod 20. The gap 36
9 between the outer surface 37 of the bend rod 20 and the inner
10 surface 39 of the mount assembly 32 is selected so that, at a
11 certain maximum curvature, the bending of the bend rod 20 is
12 limited by the mount assembly 32 and so that the optical fibers
13 18 and the detection devices 22 within the bend rod 20
14 experience no further strain at smaller bend diameters. This
15 maximum operational curvature is set so that each of the
16 curvature sensors 12 will sense across the entire range of
17 curvatures encountered during actual towing, but the maximum
18 operational curvature is much less than the curvature seen in
19 the handling system. This limitation allows the optical fibers
20 18 in the bend rod 20 to be placed further apart and still
21 survive, leading to greater strain sensitivity for the system.
22 This limitation also limits how far in wavelength the detection
23 devices 22, such as the gratings or lasers, shift.

1 If desired, in an alternative embodiment of the present
2 invention, a number of different detection devices 22 can be
3 placed on each optical fiber 18. The detection devices 22
4 placed on each optical fiber 18 can be operated at different
5 wavelengths if desired. With a smaller wavelength shift range,
6 these wavelengths can be spaced more closely, allowing more
7 detection devices per optical fiber.

8 Referring now to FIG. 3, a curvature sensor 12 is shown
9 that replaces the plurality of optical fibers 18 positioned
10 within the bend rod 20 with a single optical fiber 18'. As can
11 be seen in this figure, the optical fiber 18' has a serpentine
12 configuration with legs 40, 42, and 44. Incorporated into each
13 of the legs 40, 42, and 44 is a detection device 22. As before
14 the detection device 22 in each leg 40, 42, and 44 can be an
15 optical fiber Bragg grating or an optical fiber Bragg grating
16 laser. As the array 14 is bent, the leg closest to the bend
17 will experience compression while the leg farthest from the bend
18 will experience an increased strain. Again, by measuring the
19 changes in wavelengths in the detection devices 22, one can
20 determine the change in curvature of the array 14. One of the
21 advantages to this embodiment is that by including a plurality
22 of detection devices 22 in a single optical fiber 18, less
23 splices are required to connect the curvature sensor 12 into a
24 system.

1 FIG. 4 illustrates a modified mounting assembly 46 for a
2 curvature sensor 12. The mounting assembly 46 is a cylindrical
3 structure 47 designed to leave the center 48 of the array 14
4 free. The cylindrical structure 47 has an off axis slot 49. As
5 can be seen from this figure, the bend rod 20 with the optical
6 fibers 18 is positioned off axis in the slot 49. This leaves
7 the center 48 free for some other use. This mounting assembly
8 46 configuration does however reduce the distance that can be
9 achieved between the optical fibers 18 in the bend rod 20.

10 Referring now to FIG. 5, an embodiment of a curvature
11 sensor 12 is shown which replaces the bend rod 20 by a hollow
12 bend cylinder 50 with embedded optical fibers 18 having embedded
13 detecting devices 22. As before the detection devices 22 may be
14 an optical fiber Bragg grating or an optical fiber Bragg grating
15 laser. In this embodiment, the mount assembly 52 is located on
16 the inside of the cylinder 50. The outer diameter of the mount
17 assembly 52 is designed to be tight fitting to the inner
18 diameter of the bend cylinder 50 so that the maximum bend of the
19 optical fibers 18 is limited. This embodiment allows the
20 optical fibers 18 with the detection devices 22 embedded therein
21 to be placed further apart, thus giving greater curvature
22 sensitivity in the same array diameter.

23 As can be seen from the foregoing discussion, the present
24 invention provides a means for fiber optic sensing of the

1 curvature of a towed array. The sensing means is simple and
2 relatively inexpensive. If desired, the curvature sensor of the
3 present invention may be multiplexed with many other such
4 sensors on a single optical fiber.

5 The dynamic range of the curvature sensors 12 of the
6 present invention is limited so that it just meets the
7 requirements of the system. This allows the curvature sensor 12
8 to be designed for maximum sensitivity without risk to the fiber
9 during small diameter bending in the handling system. This also
10 allows different wavelength channels to be spaced more closely,
11 leading to more curvature sensors on each optical fiber.

12 While the curvature sensors of the present invention have
13 been described as having one, three or four optical fibers, it
14 should be recognized that more than four fibers can be used in
15 each sensor if desired.

16 It is apparent that there has been provided in accordance
17 with the present invention a fiber optic curvature sensor for
18 towed hydrophone arrays which fully satisfies the objects, means
19 and advantages set forth hereinbefore. While the present
20 invention has been described in the context of specific
21 embodiments thereof, other alternatives, modifications, and
22 variations will become apparent to those skilled in the art
23 having read the foregoing description. Therefore, it is
24 intended to embrace those alternatives, modifications, and

1 variations that fall within the broad scope of the appended
2 claims.

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